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A Review on Wind - Driven Cross - Ventilation Techniques Inside Single Rooms

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Abstract: ***Cross-ventilation, techniques can be affected by the different wind conditions. In the weak wind velocity with the moderate temperature, small widths of the inlet openings in accordance with the large outlet openings or the total widths of the windward sides, the inlet and outlet openings are in the center of these sides, collect or wing walls can be used; rectangular shapes of the indoor spaces are suitable for weak wind velocity, and short paths of air flow or air movements between the inlet and outlet openings are suitable for moderate temperature. In the strong wind velocity with the hot temperature, large widths of the inlet openings in accordance with the small outlet openings or the total widths of windward sides are applied. The inlet and outlet openings are the opposite corner of these sides or the inlet openings face. The outlet openings walls, square shapes of indoor spaces are desirable. Screen walls of the inlet openings can be used in the high wind velocity and long paths of airflow or air movements between the inlet and outlet openings are suitable for this condition. The objective of the current study is to achieve thermal comfort by wind-driven cross-ventilation techniques inside single space in four wind conditions of velocities with temperature; strong wind velocity with moderate or hot temperature; and weak wind velocity with moderate or hot temperature. To achieve thermal comfort by acceptable indoor air velocity, the study focuses on dimensional and locational relationships in both the inlet to outlet openings and the openings to their sides of the indoor spaces beside the orientations of the inlet openings to wind direction and the additional external parts of the buildings at the inlet openings such as wing or collect walls or screen walls. The dimensions of the width and depth sides of the indoor spaces in accordance with wind direction are presented also in this study.***

Keywords: Wind driven, Cross-ventilation techniques, Single room space, Outdoor wind conditions, velocity and temperature and hot regions

1. Introduction

Wind-driven cross-ventilation with its indoor air velocity can create healthy indoor environment inside space. Besides achieving thermal comfort, wind ventilation can improve air quality and can reduce energy consumption. However, indoor air velocity should be adjusted to achieve comfortable rates of velocity and temperature inside spaces. Cross-ventilation techniques can achieve this wind velocity adjustment within the inside spaces.

To achieve this adjustment, the current study focuses on a review of cross-ventilation techniques. To determine the cross-ventilation techniques under different wind conditions in accordance with indoor velocity and temperature, the study presents the relationship between cross-ventilation, indoor air velocity and thermal comfort in its first section. The second section presents a brief review of cross-ventilation techniques and the effect of outdoor conditions on these techniques in sever windy hot regions and moderate windy hot regions. The third section deals with the effect of the cross-ventilation techniques on the indoor air velocity and how to adjust this velocity in accordance with outdoor wind conditions. The fourth section shows the results and discussion that aim to achieve the integration between the second section that presents the effects of outdoor conditions on cross-ventilation techniques and the third section that presents the effects of the different techniques on indoor air velocity based on the first section. Methodology of cross-ventilation techniques in accordance with outdoor wind conditions that loosed on architectural designs is presented in the fifth section i.e. Recommendations. Difference in the sizing and locations of openings with extend parts and in the dimensions of indoor spaces are presented in the last section i.e. Conclusions.

2. Thermal comfort and cross-ventilation techniques

2.1. Theory of passive cooling in different hot regions

The passive cooling by cross-ventilation deals directly or indirectly with the human body. Direct cooling can be divided into two methods. In the first method, cooling is achieved by natural convective from the building occupants to the indoor air. This method is suitable when the outdoor temperature is less than both the indoor temperature and the maximum limitation of thermal comfort 26ºC, Givoni (1994), [1].While in the second method, comfort is achieved by increasing the evaporation rates from the human body to achieve cooling, Osman (2011), [2]. This is done by increasing the air speed or air movement around the body. This method is suitable when the outdoor wind temperature is more than 26ºC. Increasing the air speed increases the convective heat loss and the evaporation rates from the human body. The air velocity, within the ventilated space is the main controlling factor that controls the effectiveness of this approach. For a humidity that is less than 70%, every 0.15 m/s can compensate 1^0C in the indoor air temperature, Osman (2011) [2], Santamouris et al (1996), [3]. The acceptable indoor velocities are 1-2 m/s for temperatures up to 33^0C, Osman (2011), [2], Toftum (2004), [4], Givoni (1998), [5]. Givoni (1994), [1] proposed that indoor air velocities, 1 m above floor, should be approximately 35-50% of the outdoor wind speed.

In the second approach, sometimes referred to as nocturnal or nigh purge ventilation, comfort is achieved via the indirect cooling effect. This is achieved by allowing the night cool air to infiltrate inside the building to cool the thermal mass of the building. In this approach the indoor air temperature is reduced during the succeeding daytime, Osman, 2011, [2], Givoni, 1998 [5], Givoni, 1994, [1], Kirshan, 2001, [6] and Watson et al, 1983, [7]. The night ventilation rates, building exposed area, the thermal conductivity and heat capacity of building material, and the diurnal temperature range, ΔT_{DR}, Givoni 1994 [1], Santamoris et al 1996[3] and santamoris et al 1998[8] are the main controlling factors that controls the effectiveness of this approach. Givoni 1994 [1] proposed that, for high thermal mass buildings and modest heat gains, the maximum indoor temperature could be less than the maximum outdoor temperature by approximately 0.35-0.45ΔT_{DR}. For high thermal mass buildings, Shaviv et al.2001 [9] proposed Eqs. 1-3 to predict the reduction of the maximum indoor temperature, ΔT_{max}, for 20 ach, 5 ach and 2 ach night ventilation rates, respectively.

$$\Delta T_{max} = 0.810\ \Delta T_{DR} - 1.627 \quad (1)$$
$$\Delta T_{max} = 0.697\ \Delta T_{DR} - 1.722 \quad (2)$$
$$\Delta T_{max} = 0.599\ \Delta T_{DR} - 1.436 \quad (3)$$

2.2. Comfortable indoor air velocity

This sub-section presents the effects and limitations of indoor air velocity on achieving passive cooling in hot regions by apparent sensation as in direct passive cooling and actual sensation as in indirect passive cooling.

2.2.1. Thermal comfort by skin sensation as direct cooling

The relationship between passive cooling sensation and wind velocity in cross-ventilation inside spaces is presented hereinafter. Tanabe and Kimura, 1989[10], and ASHREA, 2001[11], summarized the air velocities that can achieve human comfort in passive cooling according to both air temperature and relative humidity as depicted in Tables 1and Table 1 Subjective response to air motion [Tanabe and Kimura, 1989[10]]

Air velocity (m/s)	Occupant reaction
0 - 0.05	Complaints about stagnation
0.05 - 0.26	Generally favorable
0.25 - 0.5	Awareness of air motion but maybe comfortable
0.5 - 1.02	Constant awareness of air motion, but can be acceptable
1.02 - 1.5	Complaints about blowing of papers and hair but can be acceptable in living activities

Table 2: Required air velocity according to both air temperature and relative humidity to achieve thermal comfort

Air velocity (m/s)	0.2		0.5		1		1.5		2		3	
Air temperature (ºC)	27	29	29	31	29.5	32.5	31	33.5	31.5	36	32	36.5
Relative humidity (%)	80	50	80	50	80	50	80	50	80	50	80	50

Tantasavadi et al. 2001[12], investigated the required indoor air velocity according to the indoor air temperature to achieve comfort. They found that to achieve comfort at indoor air temperatures up to 30ºC indoor air velocity of 0.2m/s – 0.5m/s was required, while at indoor temperatures up to 36ºC indoor air velocity of 1.5m/s – 3m/s was required. This range of air velocities also depended on the relative humidity. Higher relative humidity decreased the cooling sensation, Rofail 2006[13], presented the effect of indoor air velocity on the apparent temperature. He reported that every 0.5m/s of air velocity can achieve 2ºC dropping in the apparent temperature, according to cooling sensation. He also indicated that natural ventilation can reduce the apparent temperature by about 10ºC at an indoor velocity of about 3.5 m/s. Chen and Ng2006[14]found that indoor air velocity 1.5m/s can achieve acceptable indoor conditions up to 33ºC.Liping and Hien 2007 [15] showed that an indoor air velocity from 0.8m/s – 1m/s, thermal comfort was achieved under two conditions; the first condition was at indoor air temperature 34ºC and relative humidity 65%, while the second condition was at indoor air temperature 31ºC and relative humidity 90%.Kang and Carillo 2007 [16]investigated the indoor air velocity that impacts human skin. Indoor air velocity is (i) unnoticed up to 0.26m/s, (ii) pleasant from 0.25m/s up to 0.5m/s, (iii) generally pleasant but causing a constant awareness of air velocity or movement and is slightly to annoying drafty from 1m/s up to 1.5m/s, which is the upper limit of indoor air velocity. Zhang et al. 2007 [17] showed that an indoor velocity of 0.7m/s can achieve acceptable indoor conditions at 29ºC. ASHREA 2004 [18] indicated that the indoor air velocity can extend up to 1.5m/s in the hot regions. Commonly, Maarof and Jones 2009[19] pointed out that at high indoor temperatures ≥ 30ºC and high relative humidity≥ 70%, continuous air velocity or movement is more important than undesirable condition of air drafts.

According to Givoni's, 1969 [20] experiments in single spaces that have two openings at opposite sides, the average indoor air velocity is 40% of wind velocity. Thus, wind velocity from 3m/s to 4m/s is desirable in accordance with comfortable indoor air velocity that can extend up 1.5m/s. Cross-ventilation techniques can adjust the inflowing wind velocity to indoor spaces to achieve the required indoor air velocity according to the previous factors.

Table 3: A summary of recommended indoor air velocity

Source	Description
Givoni (1994) [1]	Direct passive cooling can be achieved only when outdoor air temperature equals or less than 26ºC and indoor air temperature is more than 26ºC. Airflow rate between the two opposite openings are main indicators besides outdoor air temperature.
Kang and Carillo (2007) [16]	Comfortable indoor air velocity can be determined based on human skin. Minimum indoor air velocity equals 0.3 m/s. Comfortable indoor air velocity is 1 m/s. Possible maximum indoor air velocity in 1.5 m/s. This maximum value is a limit of air velocity even though thermal comfort needs more than 1.5 m/s.
ASHREA (2004) [18]	Thermal comfort can be extended from 26ºC to 29ºC, at indoor air velocity of 0.7 m/s and up to 33.5ºC, at indoor air velocity of 1.5m/s as the upper possible limit. Air velocity is the main indicator in this definition.
Rofail (2006)	Indoor air velocity can decrease the apparent

Source	Description
[13]	temperature by 10ºC if air velocity equals 3.5 m/s. Thermal comfort is preferable more than uncomfortable air velocity in the hot times.
Maarof and Jenes (2009) [19]	Continuous air movement is more important than undesirable conditions of air draft in particular at indoor relative humidity ≥70%.

2.2.2. Thermal comfort by actual sensation as indirect cooling

Reduction of indoor air temperature depends on outdoor and indoor conditions, such as air velocity and air temperature. Reduction of indoor air temperature can be achieved when outdoor air temperature is less than both thermal comfort temperature 26ºC and indoor air temperature, Givoni, 1994[1]. The value of this reduction is based on the wind velocity inside indoor spaces. Indoor air velocity 1m/s can decrease up to 4ºC, Santamouris et al, 2010 [21].

Indoor air velocity that equaled or that was more than 0.3m/s could decrease indoor air temperature from 4-6ºC when outdoor air temperature ranges from 21ºC - 26ºC and indoor air temperature equaled30ºC, Ohba et al, 2009 [22]. This condition occurred in nighttime. Thus, this type of ventilation is called night ventilation. Also, this method is classified as indirect passive cooling, because this method is not directly related to human skin.

3. A brief review on cross-ventilation techniques

Different cross-ventilation techniques are utilized to adjust the wind velocity inside the building to achieve the required indoor air velocity as studied in section 2. The presence of noticeable wind velocity and opened area in urban planning are essential requirements to apply cross-ventilation in buildings. This section presents a brief review of cross-ventilation techniques in buildings. Types of cross-ventilation, which range between one opening and two openings in one side, or two adjacent, or opposite sides, are discussed in this section. Effects of wind conditions on the dimensions and relative locations of the openings are also discussed. Finally, a comparative study between sever windy hot regions in Hurghada region and moderate windy hot regions in Thiland region are presented.

3.1. Requirements of cross-ventilation techniques

Two parameters are necessary to apply cross-ventilation in buildings. The first parameter is the presence of a driving force, which is the noticeable wind velocity to force the outdoor air into the building. The second parameter is the suitable surroundings of the buildings, such as open area of urban planning.

3.1.1. Wind velocity

Estimating the required wind velocity requires the following four factors;

1) The Beaufort scale, which indicates comfortable outdoor wind velocity that ranges from high air 1.5m/s to gentle or fresh breeze 5.6m/s – 7.5m/s Osman 2011[2].
2) The comfortable indoor air velocity, which is from 0.3 – 1m/s, Rofail 2006[13].
3) The indoor air velocity is 1.5m/s in hot temperature regions, Rofail 2006 [13].
4) The average of indoor air velocity that is in average 40% of wind velocity inside cross-ventilation single space at the opposite side walls [Tantasavadi et al, 2007[23].

The group classification of wind velocity is done according to these four factors. Weak or low wind velocity ranges from 0.5m/s to 2m/s. Moderate or comfortable wind velocity ranges from 2m/s to 3.8m/s. Strong wind velocity is more than 3.8m/s.

3.1.2. Open area

The main aim of this sub-section is to avoid the favorable conditions resulted from driven wind and buildings. Effectiveness of wind condition divides to velocity and direction. Terrain roughness that is resulted from buildings can reduce wind velocity up to 25% or less at height 10m/s, Santamouris and Wouters 2006 [24]. This is favorable conditions for strong wind velocity according to previous sub-section.

But sequence rows of building, in accordance with wind direction, can result in unfavorable recruitments of air movements starting from the second row, oke2004 [25]; to avoid these unfavorable air movement, the distance between one row and another must be more than the height of these buildings. Slope roofs can decrease this distance, Brown, 2011 [26].

Improvement airflow of driven wind around buildings is required for cross-ventilation techniques. Wind-catcher and inner-courtyards can assist to improve natural ventilation in compact buildings instead of cross-ventilation inside the buildings.

3.2. Types of cross-ventilation techniques

Since cross-ventilation can achieve high indoor air velocities, wind driven cross-ventilation is considered more effective to achieve thermal comfort than stack effect ventilation. Cross-ventilation techniques can be classified according to the number and the relative location of the wall openings. Four different configurations, for wall openings, can be applied in wind driven cross-ventilation, as shown in Figure 1. The first configuration is a single opening at the windward side; this opening is the inlet and outlet at the same time. The second configuration has two openings in the same wall at the windward side. The third configuration has the two openings in the adjacent walls; one of them is at the windward side. The fourth configuration has two openings in the opposite walls, one of them at the windward side and the other is at the leeward side.

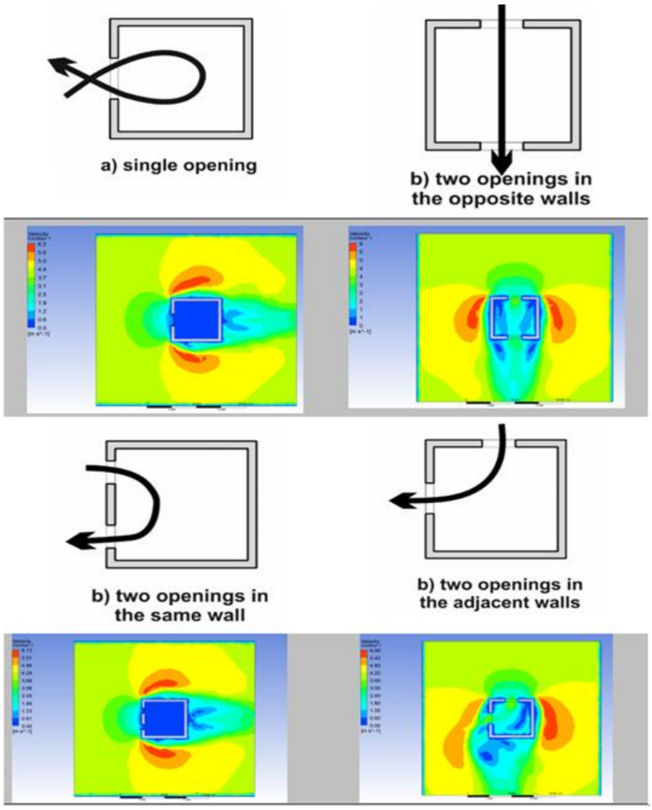


Figure 1: Cross-ventilation (in c, d) is more effective than ventilation that does not pass through the whole space (in a, b).

In the first and second configurations, adding external wing walls at the openings of the windward side increases the airflow patterns inside indoor spaces. In the second configuration, placing the openings at the two corners in the same walls is desirable to all different wind condition. The fourth configuration is the common type in most of the studies. This configuration is the main cross-ventilation technique that is suitable for all different wind conditions and passive cooling. Many secondary configurations can be branched from the third and fourth configurations. These configurations vary by altering the relative position and the widths of two openings. The main and secondary configurations can be classified by the relationship between the inlet and outlet openings in terms of location and width.

3.2.1. Objectives of cross-ventilation configurations

Each of the above configurations of cross-ventilation is used (1) to adjust the required indoor air velocity in accordance with wind conditions and (2) to direct indoor air velocity mass towards human activities inside spaces. These two methods are to avoid unfavorable impact of air velocity mass and to achieve direct or indirect passive cooling.

3.2.1.1. Adjusting the indoor velocity

The techniques used to adjustment the indoor air velocity are based on outdoor wind velocity. These techniques depend on the inlet to outlet openings width ratio, the location of the inlet and outlet openings, and the number of the inlet and outlet openings.

3.2.1.2. Directing the prevailing winds

The techniques used to direct or catch the wind are based on outdoor wind direction. Wing walls, with or without internal partitions, are one of the examples of wind catching techniques in cross-ventilation. Wing walls project outward next to a window. Adding external wing walls at the openings of the windward side increases the airflow patterns inside indoor spaces, even in a slight breeze. The use of wing walls is effective for wind direction angles from 20 to 160°, Heiselberg et al [27].

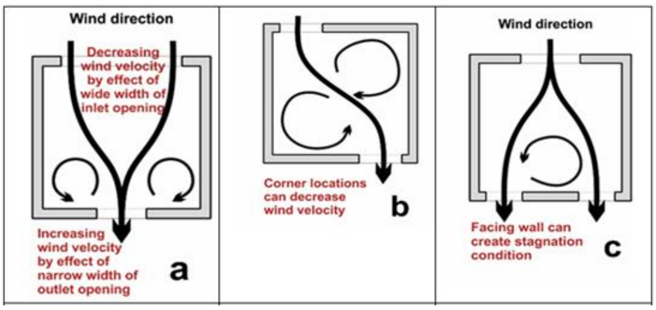
4. Location and dimensional relationships between inlet to outlet openings

In this section, the results of different studies on the location and dimensional relationships between the inlet to outlet openings are presented.

4.1. Inlet and outlet openings at the opposite sides

Figure 2 presents a comparative study for the relationship of the inlet to outlet openings in strong and weak wind velocity, Tecl et al 2013 [28]. Under strong wind conditions, the width of the inlet opening is greater than the outlet opening, as shown in Figure 2a. This helps to decrease the wind velocity at the inlet opening. Also, corner locations of the inlet and outlet openings are desirable because the wind velocity is lower at the corner locations, as shown in Figure 2b. Moreover, one inlet opening with two outlet openings are suitable for strong wind conditions, as shown in Figure 2c. The intermediate wall between the two outlet openings faces the inlet opening; this position creates a stagnation condition, which decreases the indoor velocities.

However, under weak wind conditions, the width of the inlet opening is less than the outlet opening, as shown in Figure 2d. This helps to increase the wind velocity at the inlet opening. Also, center locations of the inlet and the outlet openings are desirable because the wind velocity is higher at center locations, as shown in Figure 2e. Additionally, two inlet openings with one outlet opening are suitable for weak wind conditions, as shown in Figure 2f. This position creates the Venturi condition, which increases the indoor velocities.



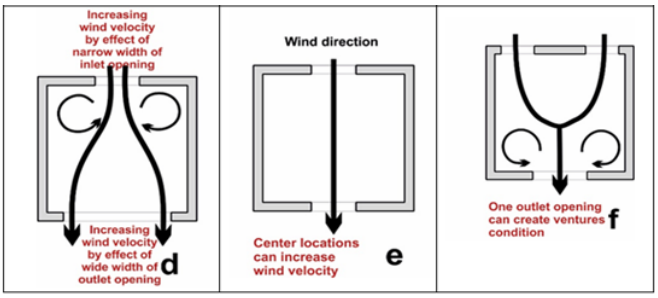


Figure 2: The relationship of inlet to outlet openings under different wind velocities

Evolo and Popov, 2006[29], compared the average indoor velocity for one-sided cross-ventilation to two-side cross-ventilation. Figure 3 shows the three studied geometries. The results of their 3-D CFD study showed that cross-ventilation at the opposite sides can achieve three times average indoor air velocity more than one-sided cross-ventilation for the same space and wind conditions, Evolo et al, 2006[29].

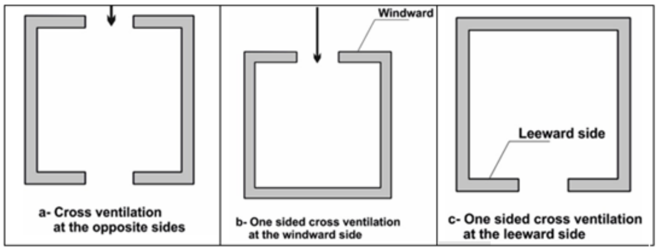


Figure 3: Comparison study between three types of cross-ventilation, [Evolo et al, 2006]

Two cases of the inlet opening's location to its side were studied by Hassan et al, 2004[30]. Figure 4 shows a comparison between the corner and the center of the inlet opening on indoor air velocity. The corner case of inlet opening can achieve noticeable ventilation area inside a space more than the center case of inlet opening.

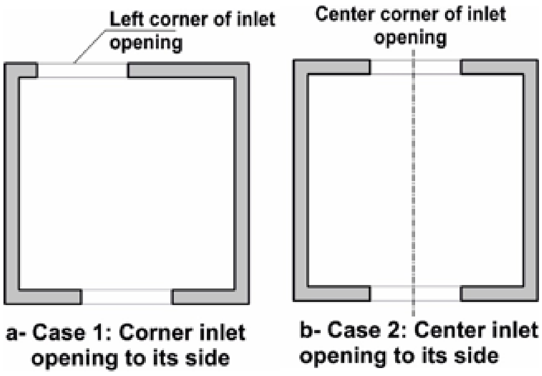


Figure 4: Effect of the inlet opening's location to its side, [Hassan et al, 2004].

Abdin, 1982[31] studied the effect of the relative location of the inlet and outlet openings in cross-ventilation on indoor air velocities, as shown in Figure 5, for two cases. In the first case the inlet opening faces outlet opening. While in the second case the inlet opening doesn't face the outlet opening. Figure 5**Error! Reference source not found.** shows that the average indoor velocities in the first case were higher than these in the second case. For example, the indoor air velocity at the inlet and outlet openings was 90% and 40% of wind velocity, respectively. While for the second case, the indoor air velocity at the inlet and outlet openings was 60% and 20% of wind velocity, respectively.

Another similar two selected cases, but in the corner openings, to show the effect of the different locations of the inlet and outlet opening, were tested by Givoni, 1969[20]. The first case was the outlet opening at the same corner of the inlet opening, as shown in Figure 6a, while the second case the outlet opening at the opposite corner of the inlet opening, as shown in as shown in Figure 6b. Figure 6 shows that the average indoor velocity in the first case was higher than that in the second case. The indoor air velocity at the inlet and outlet openings for the first case was higher. However, the second case achieved higher indoor air velocities at corner zones, which make the second case more suitable for sever windy hot regions.

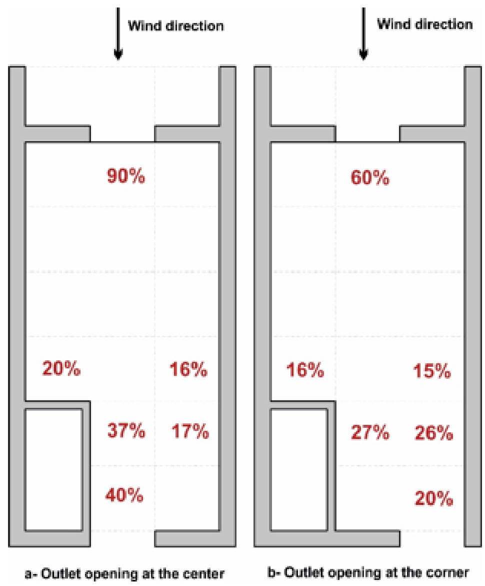


Figure 5: Effect of relative location of the inlet and outlet openings on indoor air velocity. Indoor air velocity shown as a percentage of wind speed Abdin, 1982[31]

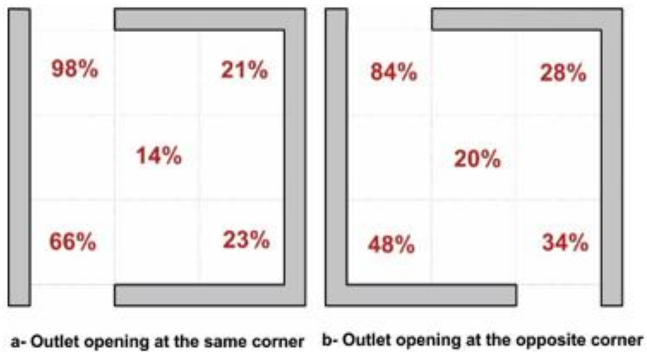


Figure 6: Effect of different locations of the outlet opening in the corner inlet opening. Indoor air velocity shown as a percentage of wind speed Givoni, 1969 [20]

4.2. Inlet and outlet openings at the adjacent sides

Adjacent openings or two openings at the adjacent sides were studied from two views. The first view focused on how to decrease wind velocity inside a space; while the second view focused on the analysis of airflow patterns according of airflow path lengths and the relationships between the airflow paths to human activity zones inside a space.

Prakasha and Ravikumarb, 2015[32], developed a 3-D computational fluid dynamics for a room to study the indoor air flow under generalized position of window openings. The results showed that relative position of the adjacent openings can decrease indoor velocity in average up to 26%, which makes this technique is suitable for strong wind starting at 4m/s.

Seifert et al, 2006[33] examined a simplified macroscopic method for predicting the ventilation flow rates for three different wind directions at different window-to-wall ratios. In the three configurations, two identical equal-area openings located in windward and side walls were used. The two openings start from the roof and leeward, as shown in Figure 7. Under these conditions, the large adjacent openings can decrease the effect of wind direction.

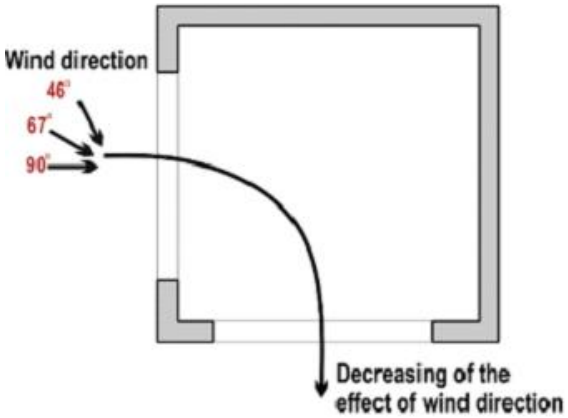


Figure 7: Adjacent opening configurations, Seifert et al, 2006[33].

[Moore, 1993] showed how adjacent openings locations can create different patterns of air flow paths, as shown in Figure 8. The figure shows that the best conditions are attained when the two openings or one of them are located at the farthest corners.

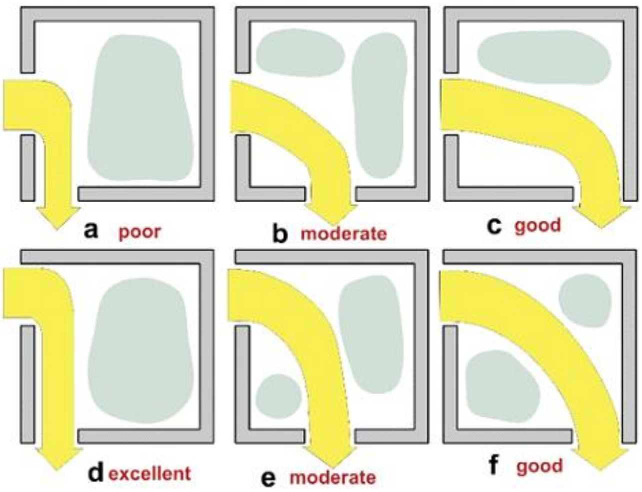
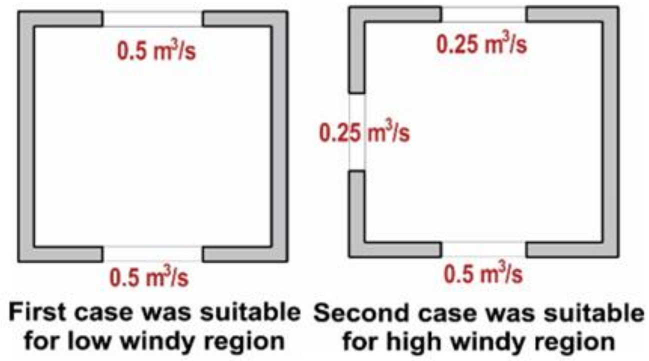


Figure 8: Adjacent opening configurations, Moore, 1993[34]

The effect of the one adjacent opening on the two opposite openings is to decrease air flow rate (m^3/s) at the outlet openings to be equaled a half value of the two opposite openings, these two cases were tested by Ohba, 2010. The first case has only two opposite openings while the second case has one adjacent opening beside these two opposite openings as shown in Figure 9a and b.



4.3. Effect of the relative vertical level

The relative vertical level of the inlet and outlet openings plays an important role in cross-ventilation. Staggered openings in the both horizontal and vertical levels at the facing opposite sides create longer air flow paths than the facing openings. Thus, these longer airflow paths of staggered openings help to achieve thermal comfort by directing air flow paths for human activities (direct passive cooling). The best case of the staggered openings in accordance to vertical level is attained when inlet opening is at the lower level and outlet opening at the upper level of leeward side, while this case in accordance to horizontal level is attained when the inlet and outlet openings are at the different corners of the facing opposite sides. Figure 10a and 10b show the staggered openings, and Figure 11a and 11b show the facing openings. The staggered openings can achieve average indoor air velocity 35% of wind velocity that is less than the facing openings that can achieve average indoor air velocity 50% of wind velocity as studied by Hawii, 2003[35] and Givoni, 1969 [20]. This lower average of indoor air velocity in the staggered openings arrangement than facing openings is suitable for low wind velocity while the facing openings are suitable for high wind velocity.

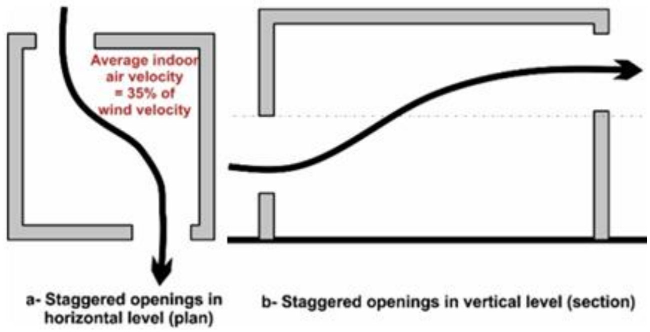


Figure 5: Staggered openings

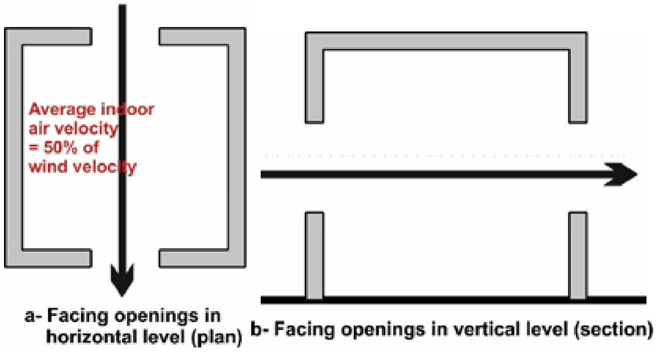


Figure 11: Facing openings

Karava et al, 2011[36] studied the effect of the relative vertical level of the inlet and outlet openings. Four cases were experimented, as shown in Figure 12. The first and second cases focused on the different locations of the outlet opening while inlet opening was at fixed center location, as shown in Figure 12a and b. The third and fourth cases focused on the different locations of the inlet opening while outlet opening was at fixed top locations, as shown in Figure 12c and d.

Figure 12 shows that for the first and fourth cases, when the openings were aligned, the average indoor air velocity was higher than the staggered cases. The average indoor air velocity for the first and fourth cases was 60% of the wind velocity, while the average indoor air velocity, for the second and third cases was 35-45 % of wind velocity.

This makes the first and fourth cases more suitable for strong wind velocity regions while the second and third cases suitable for regions with weak wind velocity. Also, the first case is suitable for enhancing direct passive cooling because air flow direct to the human activity height as a result of center location of the openings. While the second, third and fourth cases are suitable for enhancing indirect passive cooling because air flow direct far away from the human activity height as a result of top location of the outlet openings.

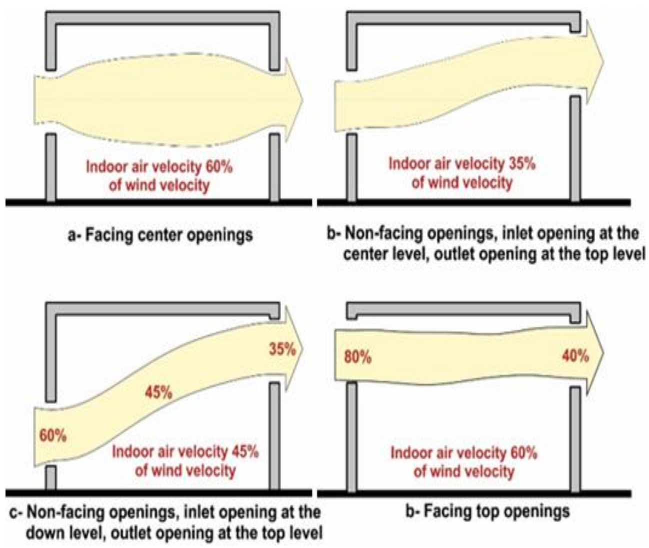


Figure 12: The effect of the relative vertical level of the inlet and outlet openings, Karava et al, 2011[36]

[Moore, 1993[34] studied experimentally the effect of different outlet opening heights, for a constant inlet opening height, on the indoor air velocity. Figure 13 shows the three experimented cases. In case 1, the inlet opening is 1.5the outlet opening height, the maximum and minimum recorded indoor air velocities were 62% and 12%, respectively, of wind speed. The average recorded velocity was 37% of wind speed, as shown in Figure 13a; this makes the design suitable for regions with high wind speeds. In case 2, the inlet and outlet openings were of equal heights, the maximum and minimum recorded indoor air velocities were 110% and 25%, respectively, of wind speed. The average recorded velocity was61% of wind speed as shown in Figure 13b, this makes the design suitable for regions with moderate wind speeds. Finally, in case 3, the inlet opening is ½ the outlet opening height, the maximum and minimum recorded indoor air velocities were 127% and 30%, respectively, of wind speed. The average recorded velocity was84% of wind speed as shown in Figure 13c, this makes the design suitable for regions with weak wind speeds.

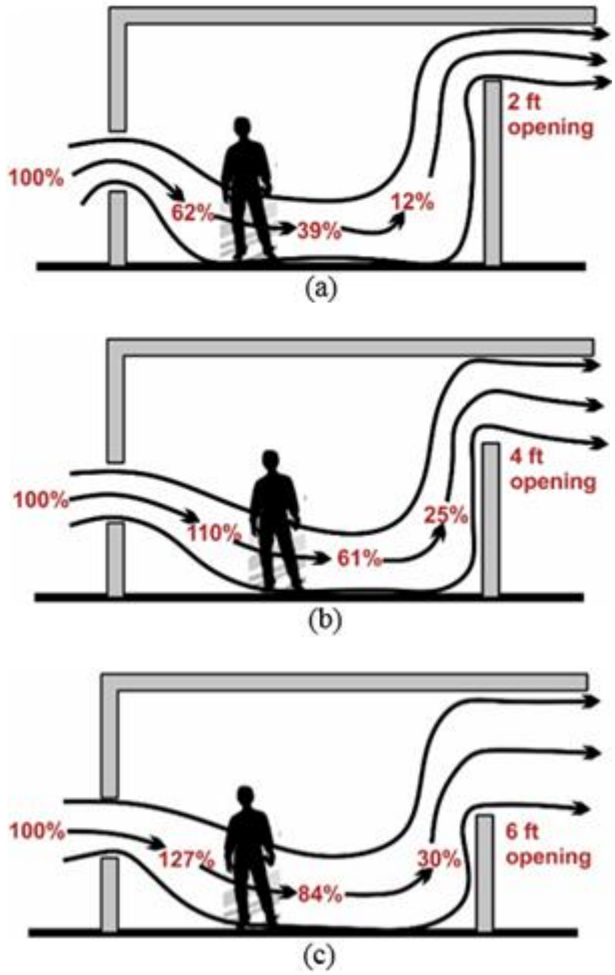
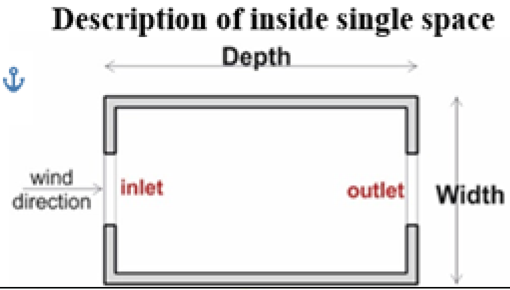
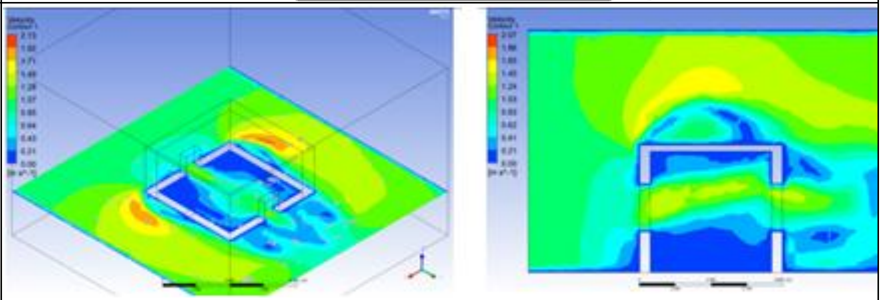
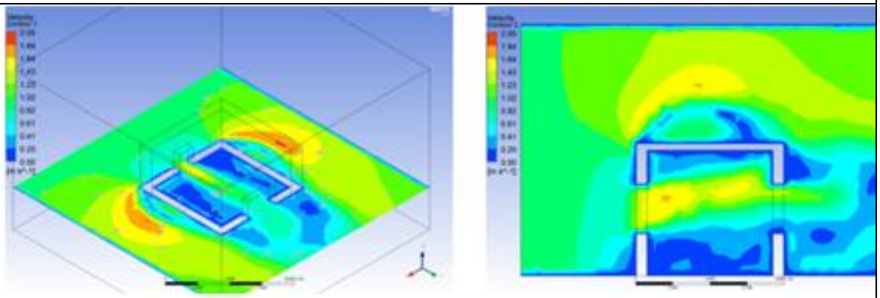
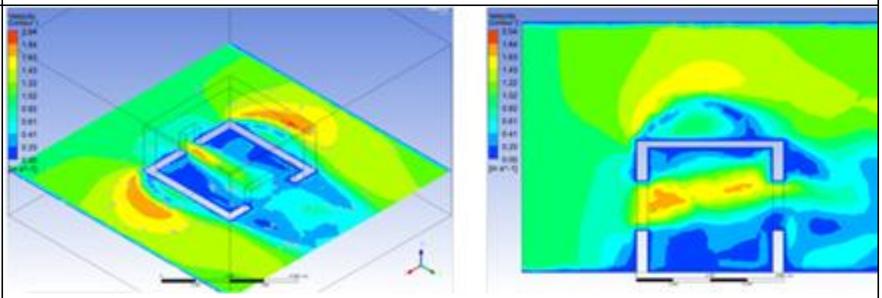


Figure 13: Height ratios between inlet to outlet openings, (a) inlet opening height more than outlet, (b) equal inlet and outlet openings heights, (c) inlet opening height less than outlet Moore, 1993[34].

4.4. Effect of the relative aperture sizes

In this section the following two relative aperture sizes are presented, for wind-driven cross-ventilation, (i) different inlet and outlet aperture sizes, (ii) equal inlet and outlet aperture sizes presents different examples on how the inlet to outlet openings width ratio and the size of the openings can change the average indoor air velocity from 30% to 50% of wind velocity [Kang and Carillo, 2007[16].

Table 4: Effect of inlet and outlet sizes in cross-ventilated spaces, *[Kang and Carillo, 2007[16]*.

<table>
<tr><th>Inlet to outlet openings width ratio</th><th>Average indoor air velocity (% of wind speed)</th><th>
</th></tr>
<tr><td>1:1</td><td>36%</td><td></td></tr>
<tr><td>1:2</td><td>39%</td><td></td></tr>
<tr><td>1:3</td><td>44%</td><td></td></tr>
</table>

Hassan, 2004[30] numerically studied the effect of the inlet window-to-wall ratio on natural ventilation in a building. The area ratios studied were 15%, 20 % and 25%of the windward façade, for two wind directions normal and 45°. Also, two locations for the inlet window were investigated; at the center and the corner of the windward façade. Their results indicated that better ventilation is achieved at 25% window-to-wall ratio. The 15% and 20 % gave almost the same ventilation level at low wind speeds.

Moore, 1993[34] studied the effect of the relative aperture size on the indoor air velocity in wind-driven cross-ventilation, as shown in Figure 14. In Figure 14a, the inlet and outlet apertures are of equal sizes. Moore, 1993[34] reported that under this condition the indoor air velocities inside the space are moderate between strong and weak.

When the inlet aperture was less than the outlet one, Figure 14b the indoor air velocities inside the space could be increased according to wind velocity. Finally, when the inlet aperture is greater than the outlet one, Figure 14c the indoor air velocities inside the space could be reduced according to wind velocity.

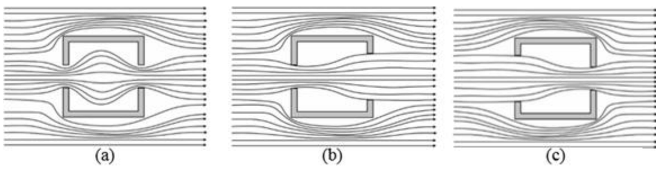


Figure 14: Relative aperture sizes in wind-driven cross-ventilation, (a) equal inlet and outlet apertures, (b) inlet aperture less than outlet one, (c) inlet aperture greater than outlet one, Moore, 1993[34]

According to Givoni's 1969 [20], experiments in single spaces that have two openings at opposite sides, for the case where the width of the inlet opening is 1/3 the outlet opening, while the width of the outlet opening equals the room length, as shown in Figure 15a. Figure 15a shows that indoor velocities at the corner of the windward wall were less than the velocity at the center of the inlet opening by about 80% and 40% for the leeward wall. The center of the inlet opening achieved 152% of wind speed while the center of the outlet opening achieves 80% of wind speed. This made the design more suitable to regions with low wind speeds.

For case 2, the width of the inlet opening is 3/1 the outlet opening, while the width of the inlet opening equals the room length, as shown in Figure 15b. Figure 15b shows that there is almost no variation in the indoor velocity next to the windward wall and the leeward wall. The center of the inlet opening achieved 62% of wind speed while the center of the outlet opening achieves 62% of wind speed. This made the design more suitable to regions with strong wind speeds.

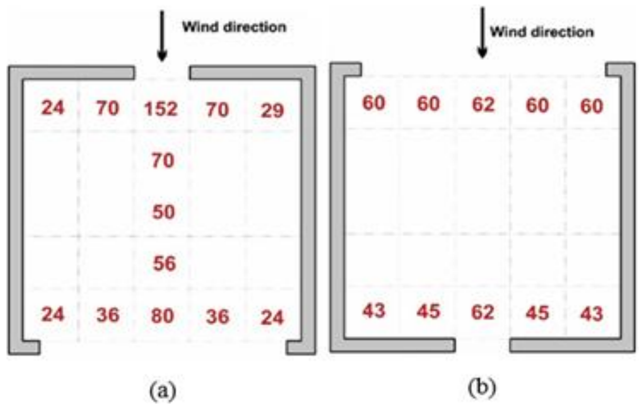


Figure 15: Effect of inlet to outlet openings width ratios. Indoor air velocity shown as a percentage of wind speed, Givoni1969 [20]

Givoni, 1969[20] further investigated the effect of the inlet to outlet openings width ratio on the indoor air velocity, as summarize in Table 5.

In these experiments the width ratio was changed by changing the width of the outlet opening, while keeping the width of the inlet opening constant. In the first case, at a 1/1 ratio, the average indoor air velocity was 36% of wind speed and the maximum was 65-102%. This made the design more suitable to regions with strong wind speeds. In the second case, at a 1/2 ratio, the average indoor air velocity was 39% of wind speed and the maximum was 92-131%.In the last case, at a 1/3 ratio, the average indoor air velocity was 44% of wind speed and the maximum was 137-152%. This made the design more suitable to regions with weak wind speeds. The same conclusions can be also drawn from Figure 13.

Table 5: Effect of inlet to outlet size ratio in cross-ventilated spaces, Givoni, 1969 [20].

Inlet opening width to outlet opening width	Average indoor air velocity (% of wind speed)	Maximum indoor air velocity (% of wind speed)
1/1	36	65-102%
1/2	39	92-131%
1/3	44	137-152%

5. Inlet Openings' Techniques

5.1. Orientation of the inlet openings relative to the wind direction

Abdin, 1982 [31] studied the effect of wind direction on ventilation effectiveness inside indoor individual spaces in cross-ventilation for three wind directions, as shown in Figure 16. In the first case, where the inlet opening is perpendicular to the wind direction, the indoor velocity is 66% of the wind velocity at the inlet opening and 37% of the wind velocity at the outlet opening. In the second case, where the inlet opening is diagonal to the wind direction, the indoor velocity is 37% of wind velocity at inlet opening and 8% of the wind velocity at the outlet opening. In the third condition, where the inlet opening is parallel to the wind direction, the indoor velocity is 1% of the wind velocity at the inlet opening and 4% of the wind velocity of the outlet opening. Figure 16 show that configuration (a) is suitable for high wind velocities, while configuration (b) is suitable for low wind velocities.

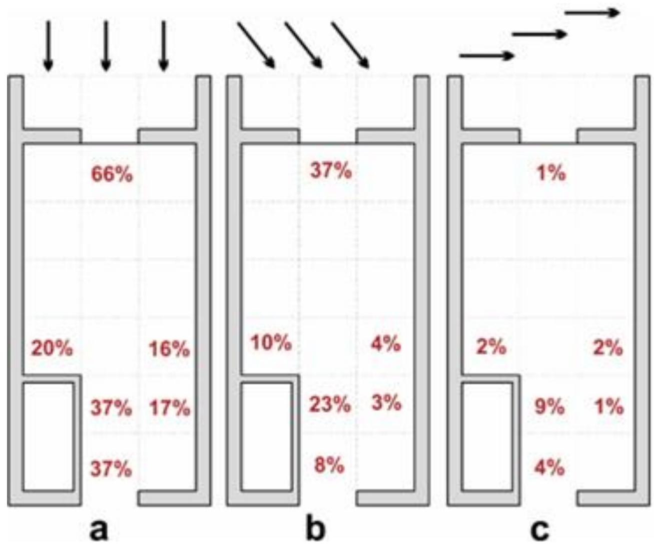


Figure 16: The effect of different wind directions on indoor air velocities

5.2. Type of the inlet openings

Inlet openings' types can affect ventilation effectiveness inside indoor spaces as shown in Figures 17 a, b, c, e, f and g, Moore 1993 [34].

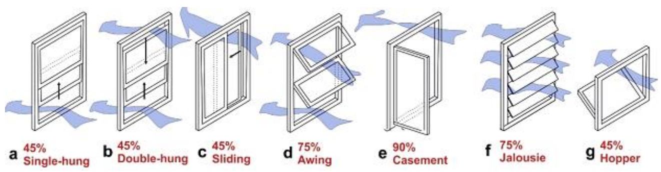


Figure 17: Types of inlet openings

5.3. External walls

5.3.1. Wing walls

Wing walls are used in either one-sided or two-sided ventilation. When wing walls are used in one-side ventilation, the opening must be at the windward side, as shown in Figure 18. When wing walls are used in two-side ventilation, the openings must be at the adjacent sides, as shown in Figure 19. In this case, the walls can or can't be faced to the wind directions; thus, wing walls are designed to catch wind from different directions.

The function of wing walls in one-side ventilation is to create cross-ventilation between the two openings that are at the same side. This is due to the creation of a positive pressure over one opening and negative pressure over the other. In two-side ventilation, the function of wing walls is to catch different wind directions. Three parameters can affect wing wall performance, such as:

1) Wind direction relative to the openings.
2) Relative distance between the openings.
3) Outside length of the wing walls.

Figures 18 and 19 show how the location of wing walls that are left or right of the openings and the distance between the openings can create air flow between these openings.

In his study on natural ventilation, [Moore, 1993] showed that configurations (a) and (c) shown in Figure 18 can achieve high performance cross-ventilation in single-side ventilation, while configurations (b) and (d) have low performance cross-ventilation. In two-side ventilation, [Moore, 1993] showed that configurations (a) and (b) shown in Figure 19 can achieve high performance cross-ventilation, while configurations (c) and (d) have low performance cross-ventilation. The same observations were reported by Brown et al [37].

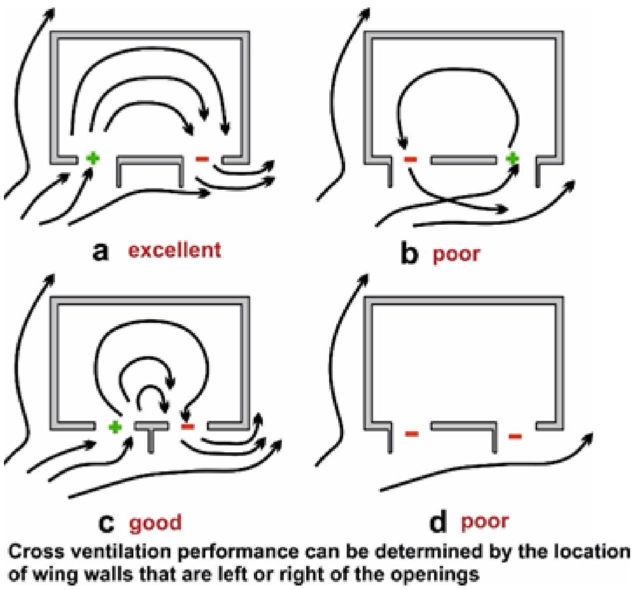


Figure 6: Wing walls on the same windward side

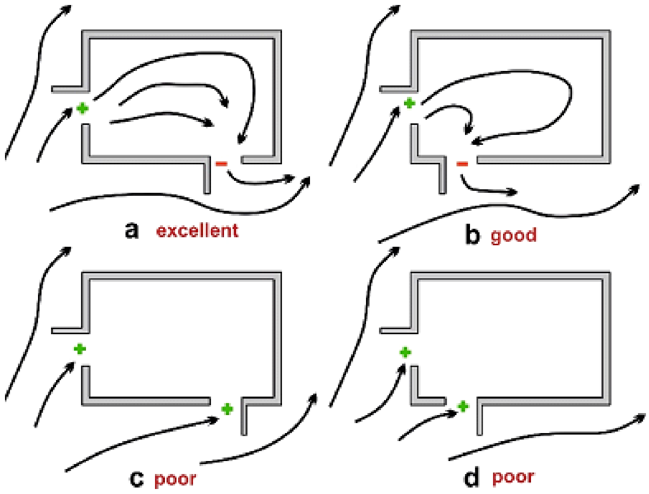


Figure 19: Wing walls on adjacent sides

Air tunnel experiments by Givoni, 1994[1] presented the effect of the wing walls on indoor air velocity. Two selected case studies were tested; the first case presented two openings at the same side without wing walls, Figure 20(a), and the other case with wing walls Figure 20(b). In the first case, the average indoor air velocity is about 8% of wind the speed. In the second case, the average indoor air velocity is about 40% of wind speed. [Khan et at, 2008[39] showed that wing walls can achieve average indoor air velocities up to 40% of the wind speed when the distance between the inlet and outlet openings is long.

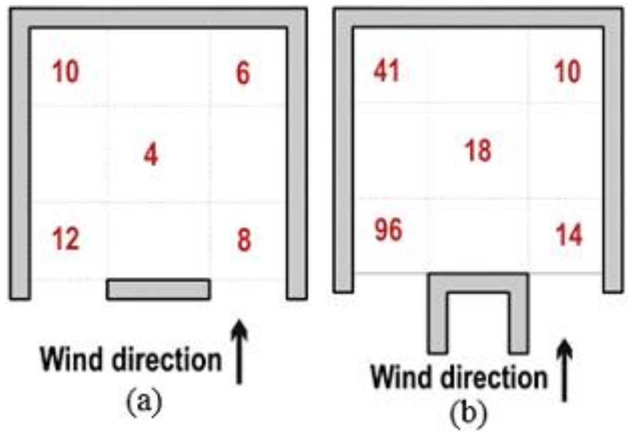


Figure 20: Effect on wing walls on the indoors air velocity, Givoni, 1994[1]

5.3.2. Collect walls

The difference between wing walls and collect walls is the relative location of the two openings. In wing-walls, the two openings are on the same windward side or at two adjacent sides. While the two openings of the collect walls are on two opposite sides, one of these sides is the windward side. The functions of collect walls are to catch more amount of wind from different directions and to increase indoor air velocity inside indoor single spaces. Thus, the collect walls can be used in unstable wind direction regions and in low wind velocity regions. Figure 21 presents three cases of the collect walls (a) collect walls are on the two sides of inlet opening to increase indoor air velocity at inlet opening, (b) the collect wall is on one side of inlet opening to catch wind from different directions and (c) no collect walls.

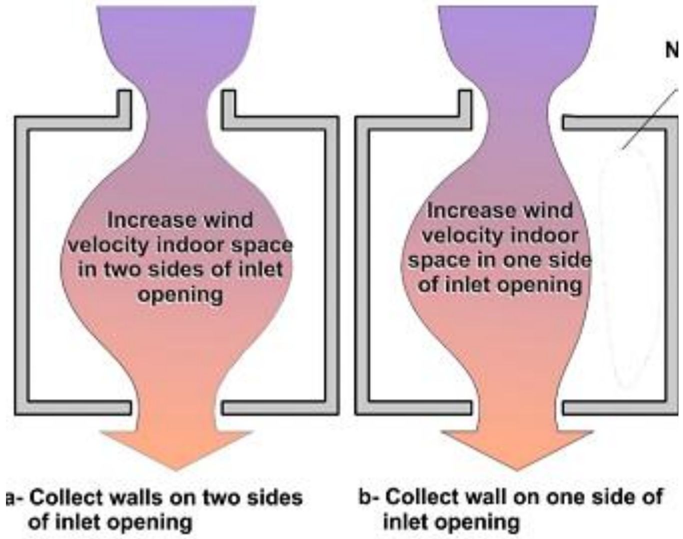


Figure 7: Collect walls at inlet openings

5.3.3. Horizontal over hung at inlet openings

The difference between the vertical wing walls and horizontal overhung is in the function, wing walls can assist to enter wind inside indoor spaces, while overhung with or without slots can direct wind from the top or the bottom in accordance with vertical level inside indoor spaces. Horizontal overhung without slots, can direct wind to the top of indoor space, as shown in Figure 22-a. Slotted horizontal overhung, can direct wind to the bottom of indoor space, as shown in Figure 22-b, [Moore, 1993].

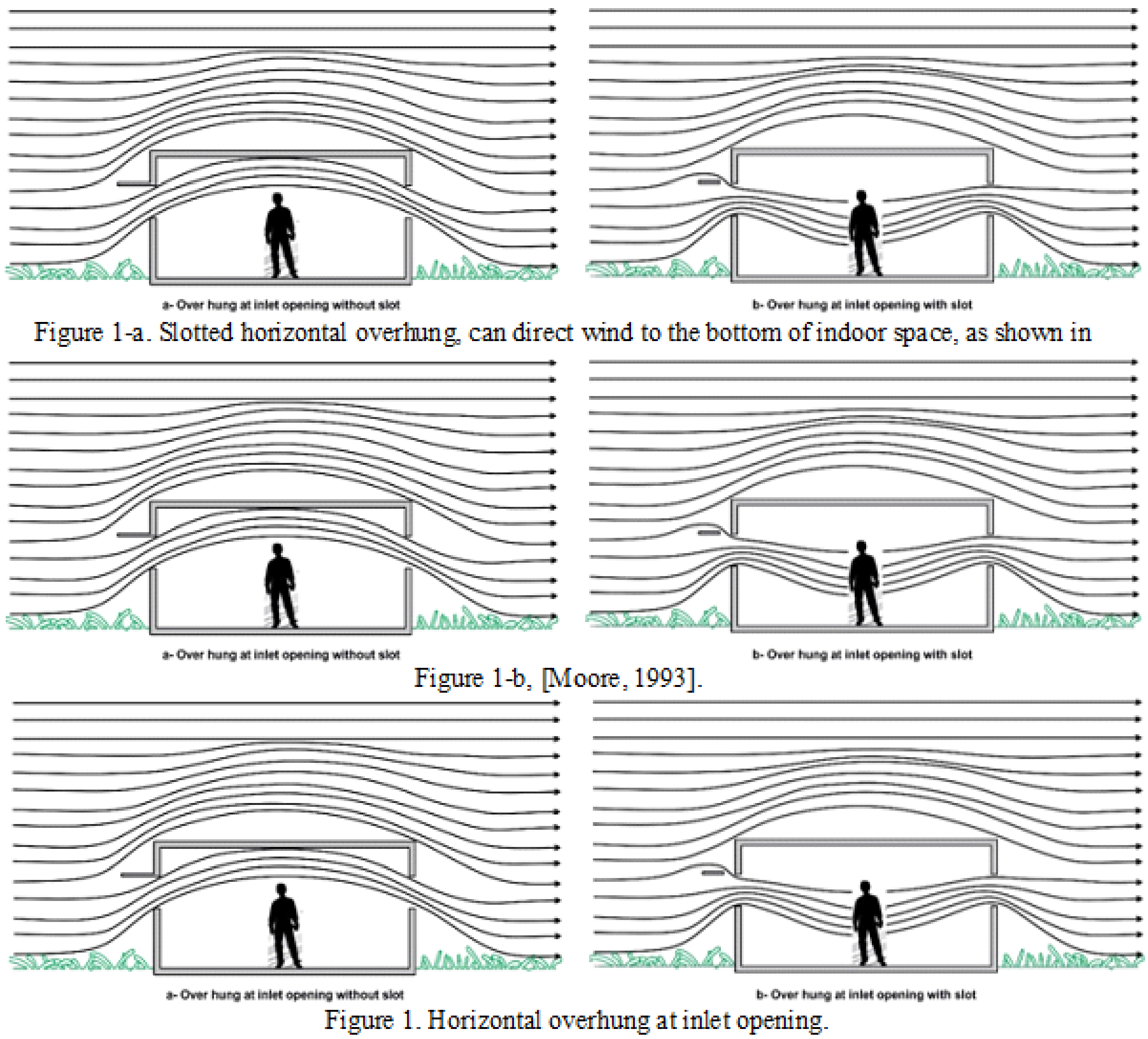


Figure 22: Horizontal overhung at inlet opening

5.3.4. Double cavity wall facades or double skin facades

The cavity of this technique that lases on down-top cross-ventilation in vertical level, works as a wind catcher. This technique can be classified to two types, as shown in Figure 23, [Poirazis, 2004[40].In the first type the double skin facade acts as outlet openings, as shown in Figure 23-a. This technique can increase the air flow rate between the top and bottom of the double skin façade. This allows more cooling wind from the inlet openings. In the second type the double skin facade acts as inlet opening which can achieve passive cooling by the difference between cool night and hot day with maximum time lag of the walls, as shown in Figure 23-b.

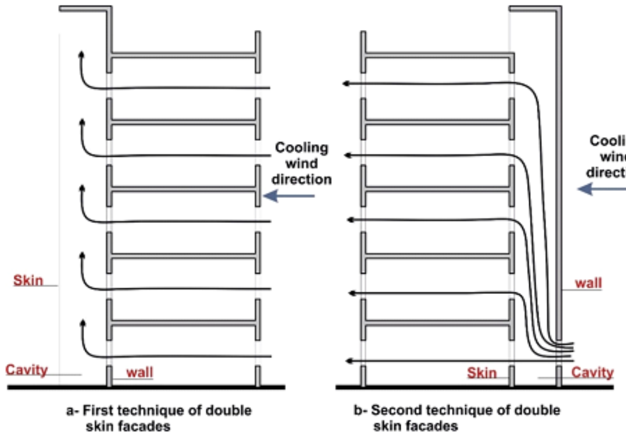


Figure 23: Double skin facades

5.3.5. Screen louvers at the opening

Screen louvers can be used to reduce strong wind velocities inside indoor spaces and to direct wind to different directions inside these spaces in the vertical level. The value of reducing wind velocity depends on two parameters, the first parameter is the distance between one louver and other; the second parameter is the direction of the louvers such as direct to the top or the down or the horizontal level, as shown in Figure 24.

Givoni, 1994 investigated experimentally the effect of inlet screen louvers on reducing the wind velocities, as shown in Figure 25. He found that cross-ventilation with equal inlet and outlet width openings on opposite sides reduced the wind velocity inside indoor spaces by 60%. Adding screen louvers reduced the wind velocity inside indoor spaces by 70-80%.

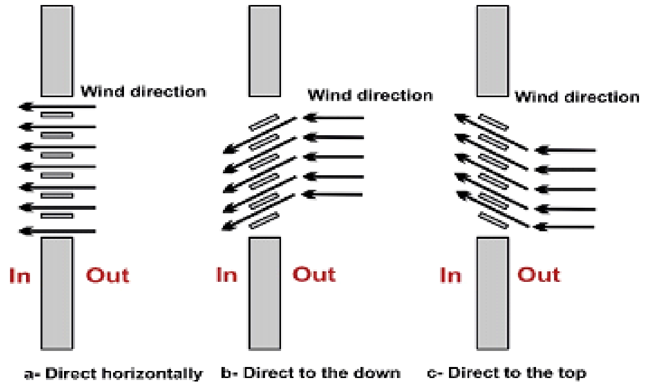


Figure 24: Section of screen louvers

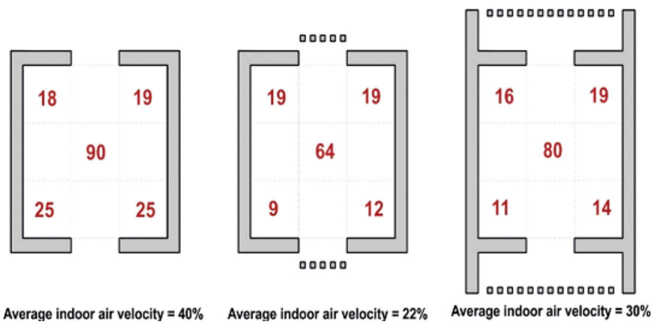


Figure 25: Cross ventilation at the opposite sides with and without screen louvers, Givoni, 1994 [1]

5.3.6. Enteral walls

The function of the internal facing walls, relative to the inlet openings are:

1) To decrease strong wind velocity inside indoor space up to 70% in the average, [Chu et al, 2013].
2) To create non-direct ventilation zones that can be occurred behind these internal walls.
3) To ventilate zones that are nearby corners that can achieve structure cooling [Moore, 1993] as a result of increasing air velocity at internal two outlet openings.

Figure 26b shows the desirable effect of enteral facing walls with inlet openings in strong wind velocities when compared to parallel internal walls, as shown in Figure 26a.

Three parameters of internal facing walls with inlet openings can be obtained from these figures:

1) Length of internal facing walls.
2) Width of internal two outlet openings.
3) Distance between the internal walls and inlet openings.

6. Application of cross- ventilation techniques in the residential buildings

Orientations according to prevailing cool wind direction and width ratios with location of the openings inside residential buildings in hot regions are the subject of this sub- section.

6.1. Multi- family buildings

Figure (27-a) shows cross ventilation techniques by width ratios of the openings in double loaded corridor building. Two sides of identical units inside indoor single spaces are around single corridor. Inlet opening width is more than outlet opening width inside indoor single spaces at the facing side as shown in Figure (27-b). While inlet opening width is less than outlet opening width at the other side to increase indoor air velocity as shown in Figure (27-c).

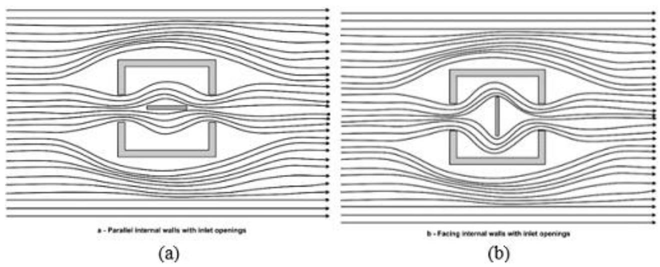


Figure 26: Internal walls as cross ventilation technique in strong wind velocity
y

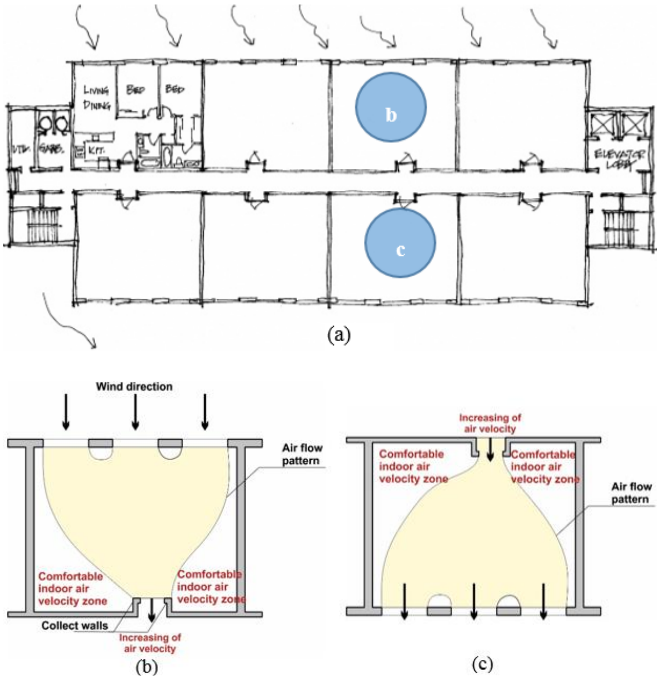


Figure 8: a- An Example of double loaded corridor for residential unit.-b and c- One room unit of the first and second leaner of a double loaded corridor[Day and Thomas, 2015[40]]

Figure (28-a) shows cross ventilation techniques by openings in single loaded corridor building. Too rectangular shapes of inside indoor single spaces of identical units are characterized this building as shown in Figure (28-b). This shape with collect walls can create ventilation condition to increase indoor air velocity inside indoor spaces as shown in Figure (28-c).

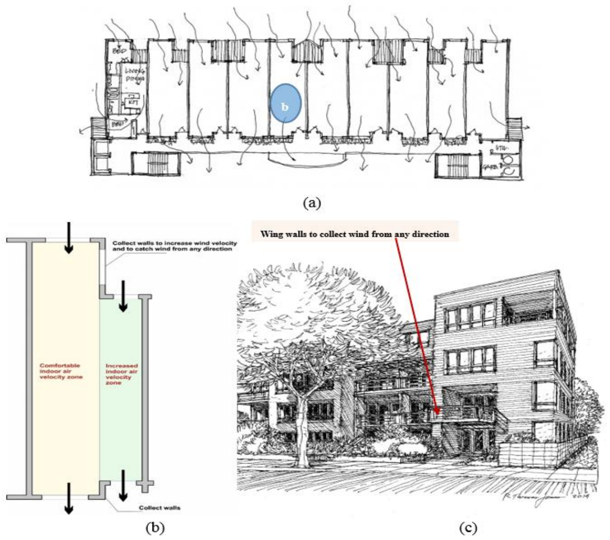


Figure 9:a-Example of single loaded corridor, b- One room unit of a single loaded corridor, c- Main elevation that faces wind direction [Day and Thomas, 2015[40]]

Figures (29-a and b) show cross ventilation techniques by the type of the openings. Casement openings can achieve area 90% of their openings' areas, while double hung can achieve area 45% of their openings' areas, [Day and Thomas, 2015[40]].

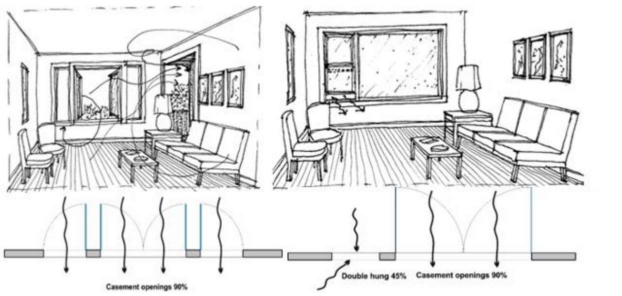


Figure 10: Types of openings according to cross ventilation techniques [Image by R. Thomas Jones, 2015]

6.2. Queensland's Residential building

Wide width of the openings with more than two openings in the one space and openings at the opposite sides are characterized as residential building, as shown in Figure (30) to Figure (34). Ventilation can be achieved in complete indoor space area in these Figures.

Figures (30 a, b and c) show how to apply cross ventilation at the opposite sides in single and double loaded corridor.

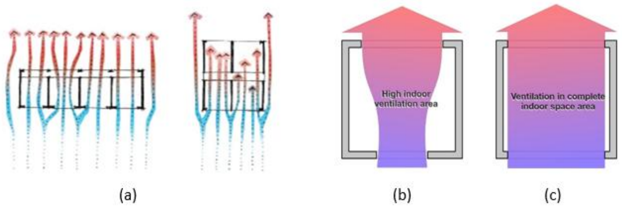


Figure 11: Single loaded corridor and double loaded corridor

Figures (31 a and b) show cross ventilation at the opposite sides inside indoor one single space.

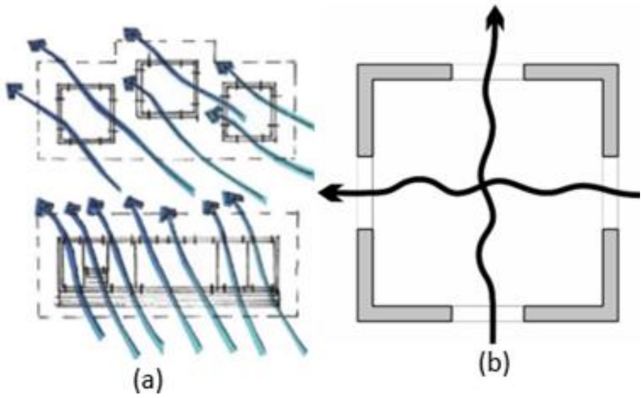


Figure 12: Cross- ventilation in single loaded corridor

Figures (32 a and b) show how the architectural design can assist cross ventilation techniques by the openings at the opposite sides.

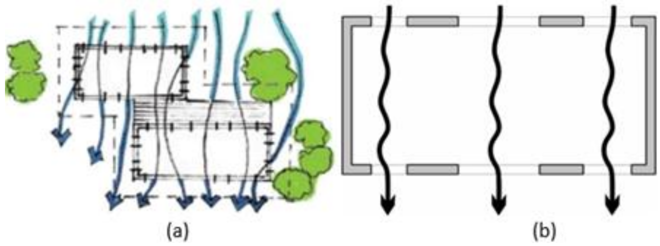


Figure 13: Triple cross ventilation paths

Figures (33 a, b and c) show how the cross ventilation adjacent sides can assist the architectural designer to achieve cross ventilation inside spaces. Cross ventilation at adjacent sides can result comfortable indoor air velocity that is pleasant impact on human.

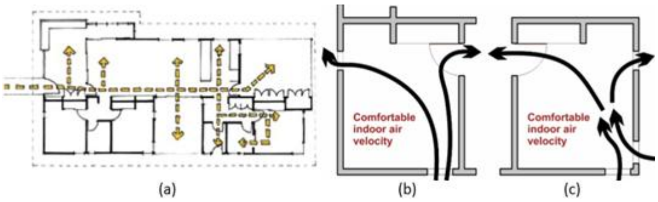


Figure 14: Cross ventilation at adjacent sides

Figure (34) shows how the collect walls can catch wind from any direction, [Smart and sustainable homes, 2015[41]].

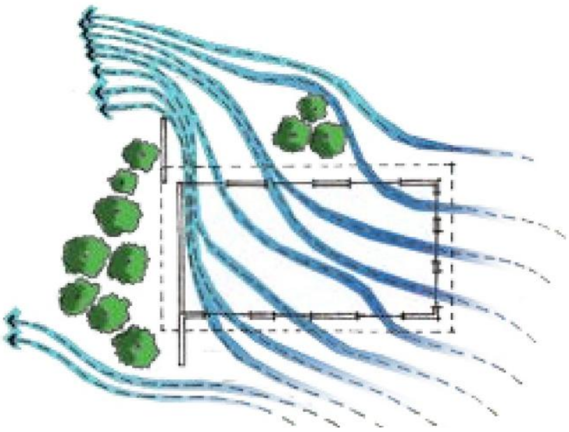


Figure 15: Collect wall catch wind from any direction

6.3. Brizalian residential buildings

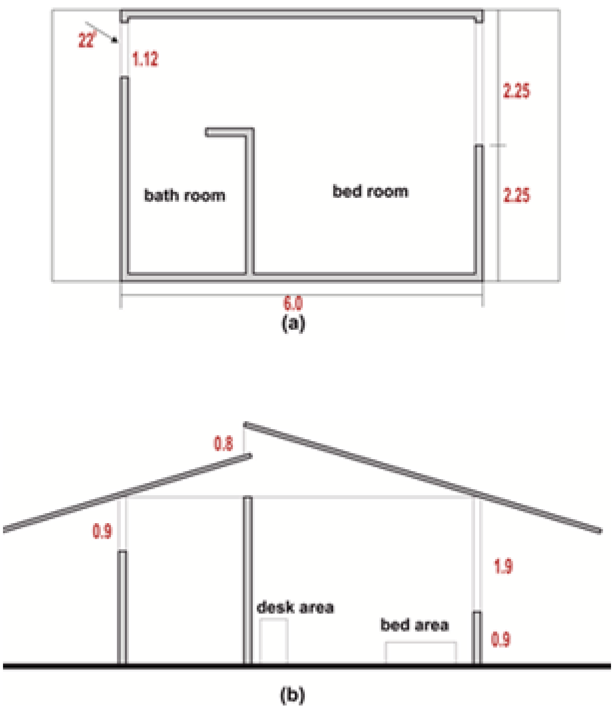


Figure 16: a) plan and b) section of southern coastal Brazilian residential buildings

This thesis presents the comparative study between inlet opening area is more than outlet opening area and inlet opening area is less than outlet opening area by changing the wind direction. The results point that the second condition that inlet < outlet can achieve indoor air velocity more than the first condition that inlet > outlet as shown in table (6).

Table 6 illustrates the effect of opening area and internal walls to adjust the indoor air velocity

Condition no.	Angle of incidence	Bed m/s	Desk m/s	Average m/s	Average of external wind velocity that is equaled 2.9 m/s
Condition 1	0°	0.33	1.1	0.72	25%
	22.5°	0.37	1.1	0.64	22%
	45°	0.22	0.22	0.22	8%
Condition 2	0°				
	22.5°	1.3	1.2	1.25	43%
	45°				

Condition 1 that inlet opening > outlet opening and internal walls of bathroom work as a strong walls. While condition 2 that inlet < outlet opening and internal walls of bathroom work as a venture walls.

7. Results and Discussions

1) Natural cross ventilation can be achieved only with the inlet and outlet openings and driven wind as the main force that must be directed to the inlet openings in the open area. Compact area is needed for the wind catchers and inner courtyards to catch the driven wind.
2) Wind velocity and temperature can affect cross ventilation techniques that based on the inlet and outlet openings such as orientations, locations and dimensions.
3) Cross ventilation techniques are different according to outdoor temperature. These techniques differ in moderate hot regions more than hot regions, such as Hurghada region. Locations and dimensions of the openings are significant techniques in the two conditions; moderate and hot. In moderate regions, the center openings can be used to achieve indirect convection passive cooling depended on maximizing indoor air velocity between inlet and outlet openings. While in hot regions, the corner openings can be used to create long air flow pattern between inlet and outlet openings that can achieve direct conduction passive cooling. Convection passive cooling is between cool wind and human skin inside indoor spaces. Thus, the width of the openings is smaller in moderate than in the hot regions.
4) Architecturally, driven wind cross ventilation by the two openings at the opposite sides can be applied in the buildings such as the studied residential buildings. Outlet openings' locations can be loaded in the single corridor. Wide width of inlet openings can assist to enter the driven wind from several directions. Collect or wing walls can be applied in particular, in residential buildings.
5) According to architectural design constrains, cross ventilation techniques divide to two types of decisions; strategic and tactical decisions. Strategic decisions can be taken in design stage while tactical decisions can be taken after the design stage.
6) Strategic decisions are such as:

- Orientation of inlet opening according to wind direction.
- Locations and dimensions of openings.
- Dimensions of spaces.

7) Tactical decisions are such as:
   - Collect or wing walls.
   - Screen walls.
   - Types of openings such as sliding openings.
8) The extended external parts of the buildings such as collect or wing walls, screen walls and over hanged roofs are affected also by wind conditions.
9) Collect walls can assist entering wind from angle direction. Wing walls can determine inlet and outlet openings when these openings are at one windward side wall. Wing walls with locations of the openings can improve air flow patterns inside indoor spaces.
10) Screen walls can adjust or can control of indoor air velocity according to dimension of their louvers. Screen wall can direct air movements to the top or the down or to horizontal levels according to types of louvers.
11) Types of the openings can modify the dimension and the locations of the openings. Also, these types can direct air movement from wind driven to the top or down in the indoor single spaces. Another cross ventilation technique can direct air movements such as over hung roofs or screen walls.
12) Double skin facades or cavity walls can be worked as wind catchers in delivering or exhausting driven wind, cross ventilation in vertical level can be occurred.
13) Cross ventilation techniques can be sorted according to the ability of adjusting indoor air velocity inside single spaces.
14) Wind orientations according to the inlet openings are the first priority. Locational and dimensional relationships between the inlet and outlet openings or locational and mathematical relationships between these openings and their sides are second priority. Dimensional relationships between windward and leeward sides to the depth sides that are parallel with wind direction are the third priority. While additional parts at the openings, such as collect or wing walls and double skin facades are the forth priority.

8. Methodology of cross-ventilation techniques

Methodology that integrates with cross ventilation techniques is divided into three parts; the first part is according to outdoor wind conditions such as velocity, direction and temperature; wind velocity is classified to three categories (weak, moderate and strong) according to Beaufort scale, direction is classified to three categories also (perpendicular / with inlet opening), temperature is classified to two categories (<= 265C or >265C) according, angle and parallel to thermal comfort. (Predict Mean Vote – PMW)

The second and third parts are according to architectural design solutions and design stages. Architectural design solutions are led to use one or two sided ventilation; two sided ventilations can be at the adjacent or opposite walls. Also, they can be led to use collect or wing walls to assist entering wind inside indoor spaces.

Architectural design stages assist in classifying the cross ventilation techniques to two categories; strategic or technical decisions, strategic decisions such as orientation of inlet to wind direction, opening conditions and indoor spaces dimensions; these techniques must be applied in design stage. Technical decisions, such as collect or wing or screen walls, can be applied in after –design stage.

8.1. According to outdoor conditions

In weak wind velocity or high outdoor temperature that is over 305c or humidity that is around 70% to achieve thermal comfort, cross – ventilation techniques aim to increase indoor air velocity depending on wind driven by Venturi effect.

According to cross ventilation techniques, methodology consists of two types of these techniques. First technique is related to the openings such as:

- Two-sided cross ventilation at the opposite walls is used inside indoor spaces.
- Wind direction must be perpendicular with inlet opening.
- Inlet opening must face outlet opening.
- Inlet opening area is smaller than outlet opening area.
- Collect wall at windward side that has inlet opening may be used to increase wind efficiency.

Second technique is related to the indoor spaces such as:

- Depth length, that is parallel with wind direction, is more than the width length that is perpendicular with wind direction.
- Inlet opening width equals or less than 1/3 of total width of indoor space.
- Locations of the openings are in the center of the windward and leeward width sides.

In strong wind velocity or low outdoor temperature that is around 305C or humidity that is around 50%, cross ventilation techniques differ than the previous techniques such as:

- One sided ventilation or two sided cross ventilations at adjacent walls
- Wind direction is angle with inlet opening.
- Inlet opening doesn't face outlet opening.
- Inlet opening area is more than outlet opening area if two-sided cross ventilation at the opposite walls is applied.
- Depth length that in parallel with wind direction, equals the width length that is perpendicular with wind direction.
- Wide inlet opening width according to total width length side of indoor space.
- Locations of the openings are in the corner in two sided cross ventilation conditions.

The techniques of strong wind aim to decrease indoor air velocity depended on wind driven by stagnation effect.

8.2. According to architectural designs

- Two – sided cross ventilation at the opposite walls is difficult in the different most designs, thus wing wall can be used in this condition.
- Angle of wind direction to inlet opening is available in the most architectural designs, thus collect walls can be used.
- Two- sided cross ventilation at the opposite walls in strong wind velocity can be found in some architectural designs, thus screen walls can be used in this condition.
- Width of the openings may be needed to adjust for several outdoor condition reasons, thus the sliding opening can be used.
- While effect of cross ventilation techniques on design concepts are such as:
- Location and sizes of the openings. Small widths of the openings are desirable in the weak wind velocity. While big width of the openings is desirable in the strong wind velocity. Center facing openings are desirable in the weak wind velocity while corner not facing openings are desirable in the strong wind velocity. The effect of cross ventilation techniques can extend to the location and sizes of the opening at vertical level, Dimensions of indoor room spaces. Square room are suitable for strong wind velocity while rectangular rooms, that the width sides are less than the depth sides, are suitable for weak wind velocity.

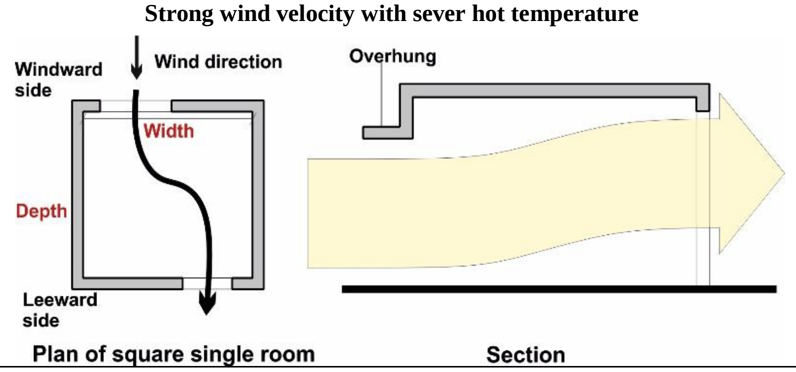
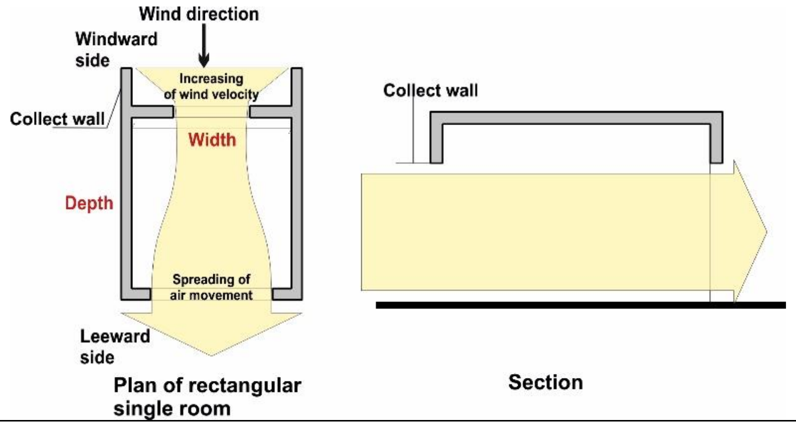
External parts can be added in the buildings such as:

- Collect or wing walls, screen walls and overhung roof.

9. Summary of cross-ventilation techniques

Four outdoor condition cases are discussed in table (8). The main aims of these cases are to achieve acceptable indoor both air velocity and temperature or to achieve thermal comfort. The four cases are evaluated according to Beaufort scales for wind velocity and to predict mean votes of the occupants inside the buildings. Thermal comfort can be achieved by two methods; one of these methods can achieved thermal comfort or cooling by outdoor cool wind when outdoor wind temperature equals or less than 265C and the other can be achieved cooling by air movement sensation when outdoor wind temperature is over 265C. Thus, cross ventilation techniques are different according to these cases.

Table 7: Four outdoor conditions with their cross-ventilation techniques

Outdoor Conditions	Cross Ventilation techniques
Strong wind velocity with sever hot temperature 	▪ Wind direction can be angle of facing inlet opening. ▪ Inlet unfaces outlet ▪ Inlet width >outlet width ▪ Inlet width = ½ total width side ▪ Width side = depth side ▪ Overhung to direct air movements to the top ▪ Air flow patterns is long
▪ Weak wind velocity with moderate hot temperature 	▪ Wind direction must be facing inlet opening. ▪ Inlet faces outlet ▪ Inlet width or area <outlet width or area ▪ Inlet width = 1/3 total width side ▪ Width side <depth side ▪ Collect wall to catch the wind from different directions ▪ Air flow is short ▪ Increase air flow at outlet
Strong wind velocity with moderate hot temperature	▪ Angle wind or facing wind according to inlet is

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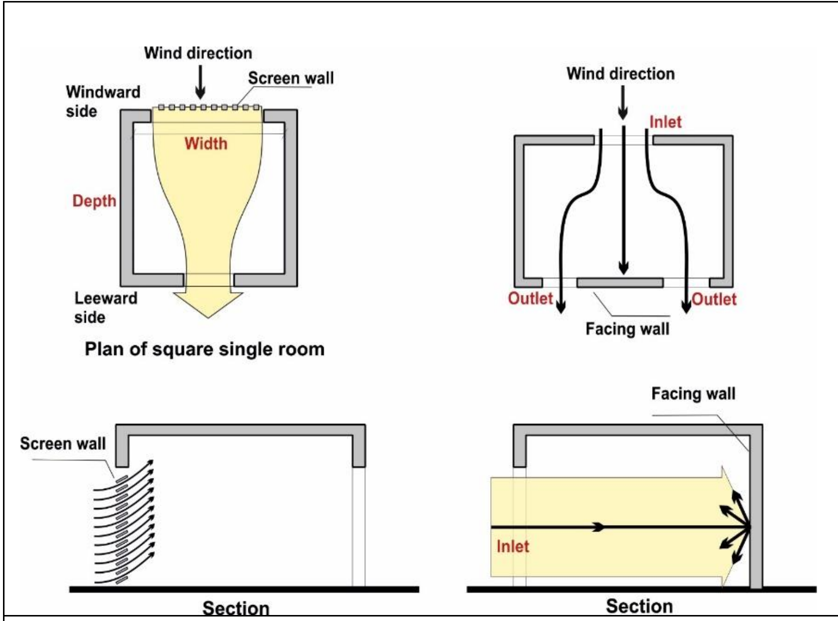

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possible.
▪ Inlet may face outlet in applying screen walls at inlet
▪ Inlet faces wall in short depth side walls
▪ Inlet width >outlet
▪ Inlet width ≥ ½ total width
▪ Width side ≥ depth side
▪ Air flow pattern has wide width according to both wide width of inlet in the first condition and facing wall in the second condition
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<tr>
<td>Weak wind velocity with sever hot temperature</td>
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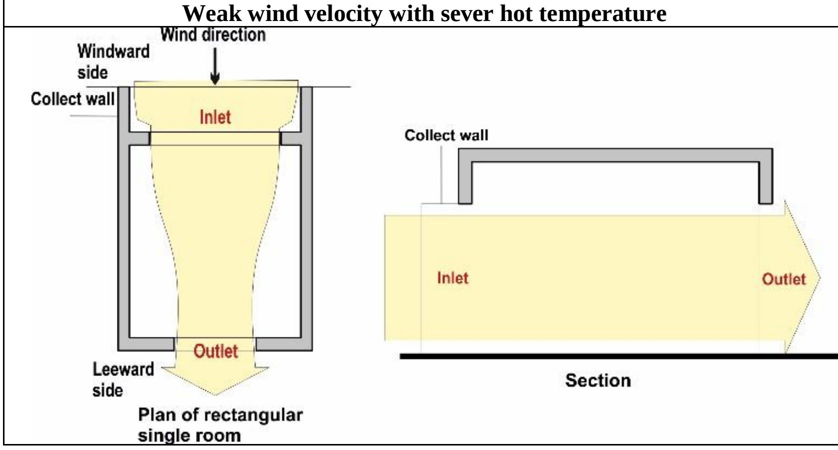

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<td>
▪ Wind direction faces inlet
▪ Inlet width >outlet width
▪ Inlet faces outlet
▪ Inlet width = total width
▪ Width side <depth side
▪ Collect wall that have the same height of inlet
▪ Air flow pattern has wide width according to wide inlet
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</table>

<u>The first case is strong wind velocity and severe hot temperature.</u>

The main aims of this case are to decrease wind velocity indoor inside space and direct air movement resulted from wind driven to the human activity zones inside the spaces to achieve thermal comfort. Thus, cross ventilation techniques are wide corner inlet that doesn’t face outlet, inlet width is more than outlet width, and width side equals or more than depth side to decrease wind velocity inside indoor single space to achieve thermal comfort by direct cooling, the airflow pattern is long, and directs to human activity zone.

<u>The second case is weak wind velocity and moderate hot temperature.</u>

The main aims of this case are to increase wind velocity indoor inside space and accelerate air movement resulted from wind driven to the outlet opening to achieve indirect passive cooling that depends on cool wind. Thus, cross ventilation techniques are narrow center inlet that faces outlet, inlet width is less than outlet width and width side is less than depth side to increase wind velocity inside indoor space by applying Venturi effect. To achieve thermal comfort by indirect cooling, the airflow pattern is short and directs to outlet opening.

<u>The third case is strong wind and moderate hot temperature.</u>

The main aim of this case is to decrease wind velocity inside indoor spaces such as the first case but in the moderate hot temperature. The difference between this case and the first case is the type of cooling. In this case, cooling depends on cool air instead of hot air to achieve thermal comfort. Thus cross ventilation techniques differ in this case than the first case. In this case, these techniques depend on wide airflow patterns in two methods, one of these methods depends on narrow outlet opening and the other depends on facing wall between two-outlet openings.

Screen walls can be used to reduce wind velocity inside indoor single space and to direct cool air at the top in vertical level. Another cross-ventilation technique that can be noticed, in the width side of single space is more than the short depth side but this condition can be applied only when inlet faces the center wall

The fourth case is weak wind, such as the second case but this case in severe hot temperature. Increasing wind velocity is required by narrow outlet or by collect wall or by rectangular shape of single room; the width side is less than the depth side or inlet faces outlet. Also, wind direction must face inlet opening because of severe hot.

Temperature: the wide airflow pattern is required by wide Intel opening and directs airflow to human activity zones.

Cross venation technique that is related to ratio between inlet and outlet is different in this case and the second case, because of the difference in temperature between the two cases.

Inlet width is more than outlet in this severe hot temperature case while inlet width is less than outlet in the previous case that is moderate hot temperature.

10. Conclusions, recommendations and future studies

1) Wind condition, such as velocity and temperature can affect cross ventilation techniques.
2) Locations and dimensions of the openings that are relative to their selves or to indoor space sides are the first priority to adjust indoor air velocity inside spaces. Beside the previous techniques, the orientation of inlet opening to wind direction is the first priority also.
3) Extended external parts that can be added such as collect and wing walls, can modify air movements; velocity and direction inside spaces.

Locations, dimensions and orientations of the openings, in particular at the horizontal level, were focused on in the previous century by Givoni (1969) and Abdin (1982). Thus, this study recommends restudying these techniques, in particular, by CFD (computational Fluid Dynamics).

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